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Reduced Gravity Gas and Liquid Flows: Simple Data for Complex Problems

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Abstract

While there have been many studies for two-phase flow through straight cylindrical tubes, more recently, a new group of studies have emerged that examine two-phase flow through non-straight, non-cylindrical geometries, including expansions, contractions, tees, packed beds and cyclonic separation devices. Although these studies are still, relatively speaking, in their infancy, they have provided valuable information regarding the importance of the flow momentum, and the existence of liquid dryout due to sharp corners in microgravity.

Introduction

Studies of gas-liquid flows have been conducted by the chemical, nuclear and petroleum industries for many years. The influence of gravity on gas-liquid flows has been demonstrated many times by simply changing the orientation of the flow direction with respect to gravity. Changes in the flow regime and its characteristics, and the pressure drop have been documented for changes as little as 0.25° between the gravity vector and the flow direction.¹ Reduction in the magnitude of the gravity vector will also have a profound effect, not only on the gas-liquid flow behavior, but also on the technologies that will be required for future space-based platforms.

The Space Studies Board for the National Research Council recently released a report documenting several technologies and fundamental science issues regarding those technologies.² The systems that require these technologies include thermal management systems, power systems, fluid management, and environmental control and life support systems (ECLSS). As such, these systems encompass a wide range of fluids from cryogenics being used for propellant and fuel cells to liquid metals for proposed space nuclear power systems. These systems will operate in gravity environment ranging from a steady-state microgravity

condition to lunar, Martian or normal gravity to transient environments greater than normal gravity such as those encountered during large rocket firings. Length scales range from micrometer-size holes found in heat pipes and those found in some proposed electronic cooling schemes to several centimeters in cryogenic and adiabatic transfer lines and space radiators.

Colin, et al.³ and McQuillen, et al.⁴ presented a review of gas-liquid flow experiments through straight cylindrical tubing. Most of these experiments have been conducted using multi-component two-phase mixtures including air and water, water-glycerin, or water-surfactant mixtures, but there have also been some experiments that have used R-12 and R134a as a single component, two-phase mixture. Abdollahian, et al.,⁵ undertook a study of system stability involving both critical heat flux and pumped loop instability using R-114. These studies were all conducted aboard various aircraft flying parabolic trajectories, which can achieve about 20 seconds of 0.01 g's . As such, it should be recognized that this method offers only a limited amount of time for the low gravity flow regime to establish itself and traverse an instrument test section, much less a complete system. Additionally, the low gravity environment aboard the aircraft is not high quality as both weather-induced turbulence and pilot skill can have a significant impact. Although several space-based experiments have been proposed, length, weight, power and data acquisition rate restrictions have either severely limited space-based testing or prevented it altogether.

Undoubtedly, while most systems will have straight lengths of cylindrical tubing, they will also incorporate non-cylindrical or changing geometries such as expansions, contraction, tees, valves, etc. This paper reports some experiments on gas-liquid flows through contractions, expansions, tees, bends, packed beds, and a cyclonic separation device.

Contractions

McQuillen⁶ conducted a series of low gravity experiments using air and water as the test fluids of flow through contractions. The entry region had a diameter of 25.4 mm with an exit diameter of 19.0 or 12.7 mm. High-speed video imaged the flow while conductivity probes were used to measure liquid film thickness and void fraction.

The transition of the flow regimes was rather revealing based on the video. As seen in Figure 1, bubble coalescence does not occur between axially displaced bubbles as the liquid between the bubbles is accelerated with the bubbles and then causes the distance between the bubbles to increase. Bubbles that are radially displaced will sometimes coalesce or may just bounce off each other. The primary transition from bubble to slug flow occurs when large spherical bubbles are radially compressed to fit into the smaller diameter as seen in the case of the lead bubble in Figure 1. These spherical bubbles must have a radius larger than that of the contracted area.



Figure 1.—Time Sequence as two bubbles flow through a 25.4 to 19 mm contraction.

Another interesting phenomena is that liquid film dryout occurred in some cases in the vena contracta area of the contraction (Figure 2). Typically, bubbles are caught in this recirculation zone and coalesces into

a larger gas pocket. As this area continues to grow, it reaches some size whereby the flow shears the gas pocket into two. One pocket remains at the vena contracta, but the other pocket is swept downstream. It is suspected that the gas pocket is held in place both by the low pressure region of the vena contracta and the pinning edge of the reduced diameter.



Figure 2.—Bubble flow through a 25.4 to 12.7 mm contraction. The dark band on contraction is where the gas is recirculating.

Taylor bubbles form a liquid bridge across the bubble as they entered the contraction. The liquid bridging is unstable and collapses downstream as the front part of the bubble apparently has a thinner liquid film around it, which slows the bubble down relative to its tail allowing its tail to catch up and coalesce. If two Taylor bubbles enter the test section and the tail of the leading bubble is separated from the nose of the trailing bubble by less than 1 tube diameter, the liquid between the two bubbles drains into the liquid film and the second bubble attempts to coalesce with the lead bubble.

Liquid slugs in general become much thinner at higher velocities and as such, gas begins to penetrate the gas bubble. Unfortunately, because the field of view was relatively short, it was not possible to view the complete transition from slug to annular flow.

Expansions

A series of tests were recently conducted aboard the KC-135 to examine the effect of gas-liquid flows into an expansion. Air and water, and air and a 50 without water-glycerin mixture were used as the test fluids. The entry section had a 12.7 mm diameter tube, and expansions with either a diameter of 19.0 or 25.4 mm were tested. Instrumentation included conductivity probes to measure void fraction and differential pressure transducers. A high-speed video imager was used.

Due to the type of mixer that was used to introduce the two phases together, it was not possible to obtain annular flow in the entry region, although a broad span of tests for bubble and slug flow conditions was conducted. Also, the mixer and the insufficient length for the flow development, test conditions that should have resulted in slug flow, actually caused bubble flow as they left the entry section and entered the expansion.

For both the slug and bubble flow conditions at low flow velocities, the flow enters the expanded region and

readily conforms to the new larger diameter. In the case of bubble flow, especially for the larger expansions that were tested, there is a recirculation zone of bubbles in the cylinder's corner (Figure 3a). Usually, a large gas pocket forms in the corner of the expanded area and remains there for a significant portion of the test (Figure 3b). For the tests involving water, the gas pocket is eventually swept downstream, while for those tests with the water-glycerin mixture, the gas pocket remains there for duration of the entire test. Regardless, this gas pocket alters significantly the flow field behind it as bubbles become trapped in its wake. For the water tests, multiple gas pockets alternate positions of being in the corner and the wake corner pocket.

At higher flowrates, a two-phase jet develops. The jet traverses through the central portion of the tube and is surrounded by the gas phase. For an entering bubble flow regime, a jet approximately equal to the diameter of the entrance section is observed (Figure 3c). The mixture of liquid and gas bubbles proceeds down the length of the test section.

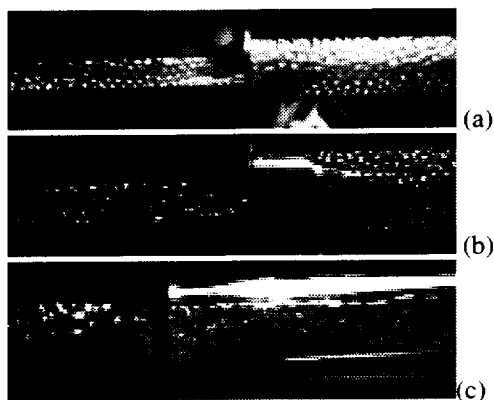


Figure 3.—Bubble flow into an expansion. (a) Flow conforms to geometry, (b) Gas pocket in corner of expansion, (c) Bubble jet in expansion.

If there were any Taylor bubbles present, the situation is different. Since these cylindrically shaped bubbles are no longer constrained radially by the tube wall, they start to expand radially and shrink axially. Figure 4 illustrates this process. These bubbles separate from the preceding, faster-moving liquid slug, thus breaking up the two-phase jet. The bubbles then slow down significantly and become a spherical shape. The spherical lobes can be either overtaken by succeeding liquid slugs or grow to the point of contacting the walls and rupturing. When a liquid slug contacts the bubble, liquid splashes onto the tube wall as the bubble ruptures. This behavior is apparently dependent on the length of the cylindrical bubble and the slugging frequency.

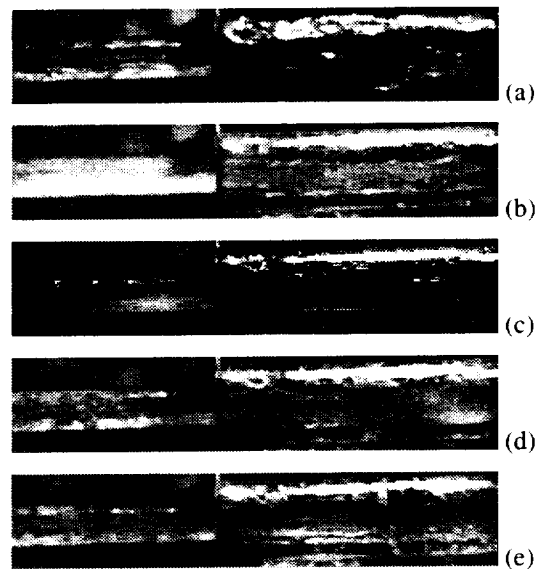


Figure 4.—Slug flow to two-phase jet. (a) Slug in entrance, (b) Slug enters empty expansion pulling thin film behind it, (c) Slug detaches from bubble, (d) Thin film forms spherical lobes, (e) Lobe contacts wall and ruptures.

For very long cylindrical bubbles, the stretching of the thin film also causes rupture of the bubble. The motion is caused by both the radial expansion and the initial pull from the preceding liquid slug before the slug had detached. Generally, after the bubble film ruptures, there is no additional liquid film motion from the entrance into the expansion since the liquid film in the entrance has already stopped moving.

The rupture of the thin film cylindrical bubbles and splashing from the liquid slug penetration of these bubbles supply the liquid for the quiescent film on the wall. The deposition of additional liquid would result in some wave motion in the film, but overall, there was very little liquid motion within this film.

Typical flow regime maps are shown in Figures 5 and 6 for the water and glycerin mixtures for the 12.7 to 19.0 and 12.7 to 25.4 mm expansions respectively. As was discussed earlier, for the slower flowrates, there is no change in the flow regime. At faster flowrates, however, there is typically the formation of a two-phase jet. The transition to jetting from the "traditional" flow regimes occurs much more readily for the larger change in diameter ratio than the smaller change. It is possible that this is due to the closer walls restrict the amount that the two-phase jet can expand radially more than the case for the larger diameter tubes. In general, the liquid flowrate seems to play a significant role in the jet formation, probably because of the high liquid density and, thus, momentum.

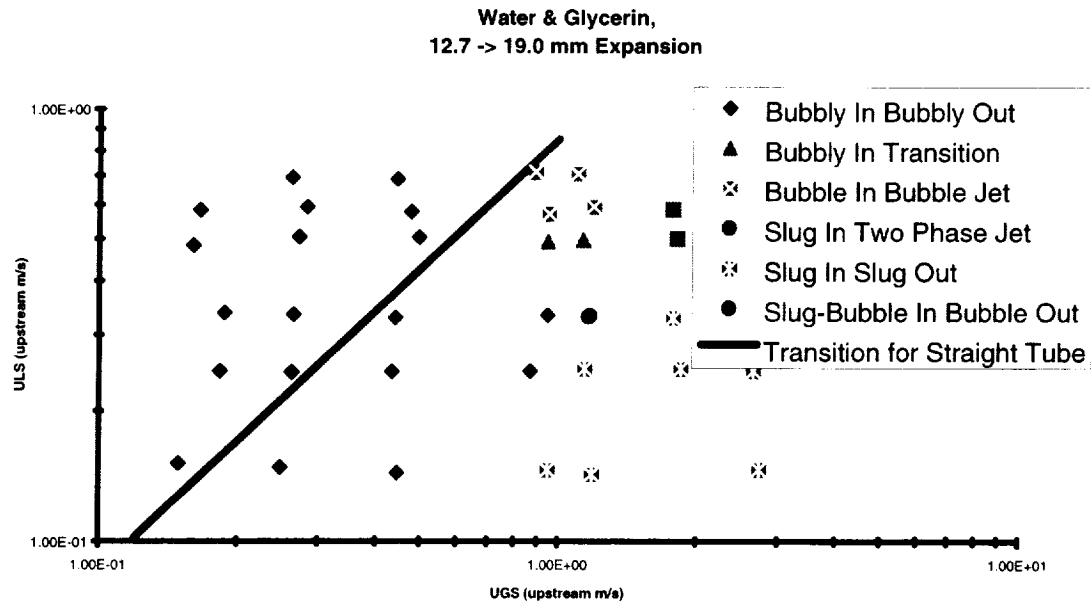


Figure 5.—Flow regime map for water and glycerin mixture and air in a 19.0 to 25.4 mm expansion.

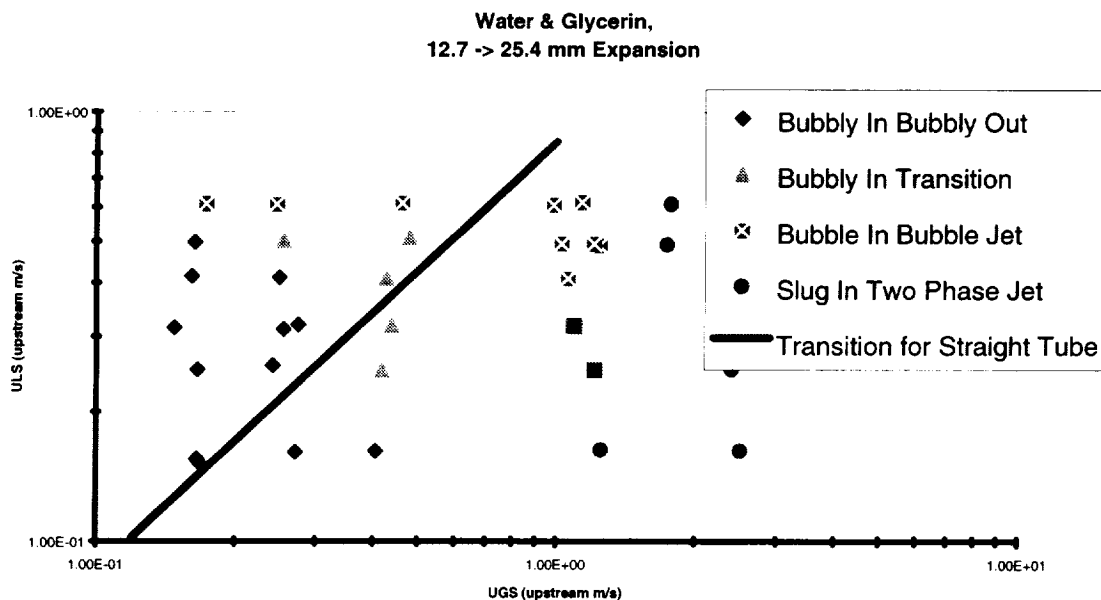


Figure 6.—Flow regime map for water and glycerin mixture and air in a 19.0 to 25.4 mm expansion.

Although this “new” two-phase jet flow regime is observed immediately downstream of the expansion, a more “traditional” flow regime, such as slug or bubble flow, was observed further downstream in the vicinity of the conductance probes. This is due in part for the slug flow because of the redeposition of liquid from the cylindrical bubble onto the wall.

Redeposition for bubble flow may be due to the jet striking the thin wires of the conductance probes and spreading/splashing out to the walls, because of the discontinuities between the two pieces of tubing that mate adjoining pieces of the test section together, or fluctuations in the residual gravity level.

Tees

Jayawardena and McQuillen⁷ conducted a series of experiments for two-phase flow through a splitting tee. The test section was 1.27 cm in diameter with flow entering on the "run" of the tee and exiting through both the "run" and the "sidearm branch." Water and a water glycerin mixture were used for the test liquids, while air was the gas phase component. Each leg of the tubing that tied into the tee was instrumented with a pair of conductivity probes and differential pressure transducers. Only the flow through the actual tee was imaged.

The gas and liquid flowrates into the tee were known prior to mixing the two phases together. In order to satisfy continuity, the flowrates of both phases needed to be measured in at least one of the exit legs. The decision was made to separate the two phases exiting the sidearm branch and measure the flowrates of both phases there. The gas phase flowed through a desiccant bed that absorbed any excess moisture before entering a thermal mass flow meter. Liquid was contained in the separator and the liquid level was measured via a sight glass on the side of the separator both prior to and after the completion of the test.

The conditions of the operating environment made it difficult to obtain a high level of confidence in the sidearm flowrates. For the liquid flowrate, liquid needed to drain towards the bottom of the separator

after the aircraft had pulled out of the low gravity parabola and prior to the start of setting up for the next trajectory. The residual acceleration levels in all three directions aboard the aircraft were not conducive for "leveling" the sight glass with the separator. These two factors coupled with the high experiment operator workload did not give confidence in the ability to obtain an accurate liquid flowrate. In addition, the liquid flowrate was a "batch" flowrate in that it was nothing more than the total mass collected during the test divided by the length of the test. There were no corrections for flow startup and shutdown.

While the gas flowrate was more reliable, there was a problem with obtaining this data as well. It was difficult to measure the lower gas flowrate because of the volumetric capacity of the separator and the pressure loss associated with flow through the desiccant bed and flowmeter. These slow air flows took a significant amount of time to generate a sufficient pressure to overcome the pressure losses and generate a flow within the range of the flow meter.

Despite these problems, several important observations are ascertained. First, from the visualization data, such as in Figure 7, it is very difficult for the liquid to turn the corner and flow down the sidearm: The preferential direction is straight. The two-phase flow in the sidearm branch is significantly different in terms of velocity and

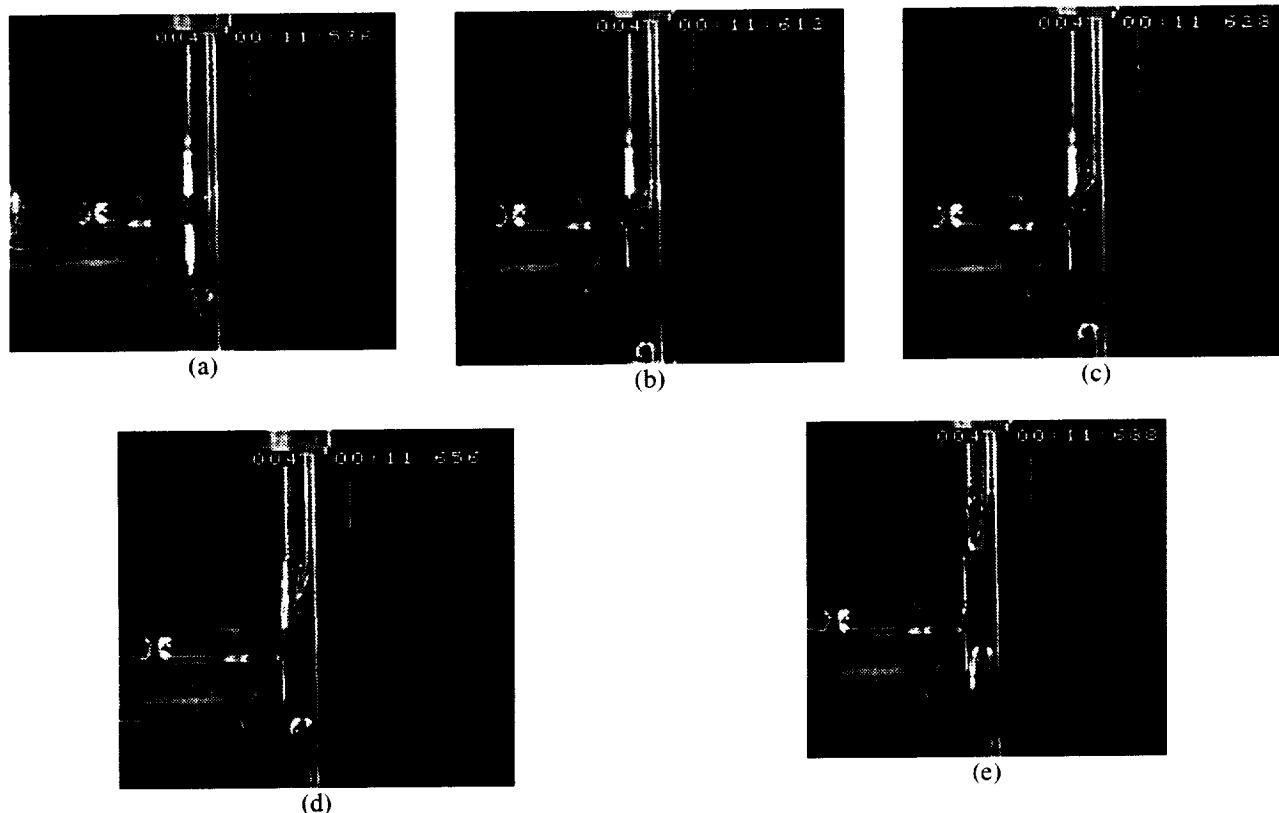


Figure 7.—Gas-liquid slug flow through a tee. Flow is from bottom to top and right to left in the sidearm branch.

structure as compared to both the entry and exit flows on the tee's run as evidenced not only by the video but also by the conductivity probe data. This occurs despite attempts to vary the flow resistances in the two legs with respect to each other via some metering valves that were positioned in each exit leg.

Finally, the last differential pressure drop in both exit legs exhibits a "pressure recovery" when compared to the pressure drop in the entry leg. This is similar to flow through an expansion due to decrease in mass flow rate because of an increase in flow area. However, in normal gravity, typically, one exit leg shows signs of a pressure recovery while the other exit leg incurs a pressure loss.

Packed Beds

To date, three independent experiments for flow through packed beds in low gravity have been conducted. In two of these studies, the primary objective was to verify sufficient mass transfer, so instrumentation specific to hydrodynamics was minimal.

One of these two, conducted by NASA MSFC, was the Volatile Removal Assembly Flight Experiment⁸ (VRAFE), which flew on STS-89 and STS-96. It was a high temperature catalytic oxidation process that included several major components, one of which was a packed bed reactor. They reported some unexpected overall pressure fluctuations, possible gas inclusion in the bed and a loss of chemical performance. Unfortunately, there was not sufficient instrumentation to fully understand the impacts of the microgravity environment.

The other mass transfer study was conducted aboard the KC-135 by NASA JSC, which was a waste-water bioreactor. This effort utilized a packed bed design consisting of Berl saddles packing with Raschig Rings, either spiraled through the packed bed or as alternating layers of the two packing materials.

The packed bed was oriented horizontally. Flow was continuous throughout the low and high gravity portions of the trajectory, but because of the orientation of the flow through the packed bed with respect to gravity, the flow was diverted to a parallel channel during the normal and high g portions of the trajectory. As the experiment would enter the low gravity period, water that had drained into the bottom of the packed bed was wicked throughout the dry area of the packed bed.

A bubble flow was injected into the packed bed. However, due to the volume of the packed bed and the initial distribution of the liquid and gas, there was an

initial surge of gas at the outlet followed by a long slug that was almost entirely liquid. Sometimes towards the end of the trajectory, a bubbly flow would exit, although the void fraction of the exiting flow was lower than the entering flow, indicating the flow was not fully developed. The bed showed signs of about 30% occlusion and a significant amount of flow channeling.

To address the hydrodynamic issues from the first two studies and to better understand the flow characteristics of this type of system, Motil et al.⁹ used a packed bed consisting of spherical glass beads with diameters of 2 mm and 5 mm. The test apparatus was designed to fly on the KC-135 aircraft with the section oriented vertically and instrumented with five differential pressure transducers evenly spaced along its length. High-speed video was also used to confirm the flow characteristics. The gas and liquid phases were mixed prior to the inlet of the column. Water-glycerin mixtures ranging from 1 to 20 cP were used and the flow rates were varied over a wide range to observe bubbly, spray (or mist) and pulse flow.

The flow pattern transition data indicates that the pulse flow regime exists over a much wider range of gas and liquid flow rates under microgravity conditions compared to normal gravity cocurrent down-flow. Figure 8 illustrates this with a widely used flow regime map first proposed by Talmor.¹⁰ The basis for the Talmor map is that a driving-to-resistance force ratio can be developed for two-phase flow through a packed bed. The driving forces are inertia and gravity while the resistance forces are viscous and surface tension. By normalizing these forces and using two-phase dimensionless numbers, he plots the force ratio versus the superficial volumetric gas-to-liquid ratio. By setting the gravity term ($1/Fr$) equal to zero, the plot should predict microgravity flow regime transitions, but in fact, the bubbly pulse transition is almost an order of magnitude lower as indicated by the solid lines.

The characteristics of the bubbly flow regime are similar in 1-g and 0-g except that the overall pressure drop across the column is higher in microgravity. The increased pressure drop is equivalent to the static head. However, it is found that in the pulse flow regime, gravity affects both the pressure amplitude as well as the overall pressure drop. Finally, in the spray or mist flow regime, there is essentially no difference between normal and reduced gravity. This is expected since the flow regime characterized by very high gas flow rates with small droplets of water dispersed throughout the packing and is dominated by inertia forces.

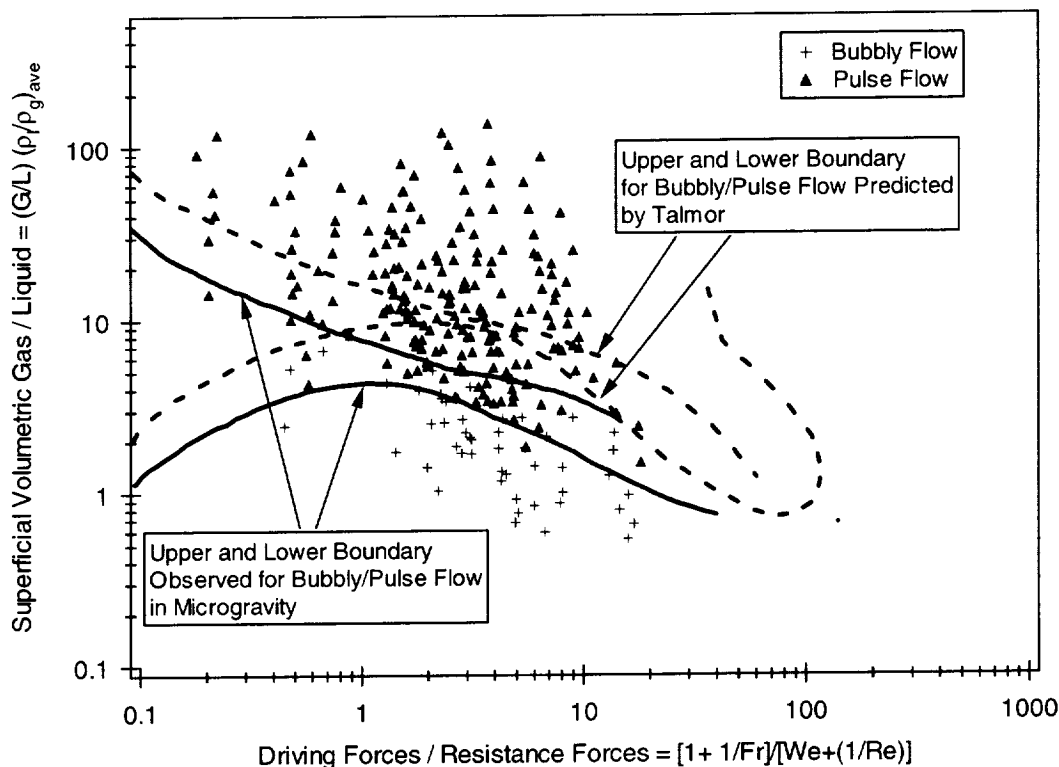


Figure 8.—Microgravity flow regime map for gas-liquid flow through a packed bed.

Cyclonic Separator

Shoemaker and Schrage¹¹ conducted both an experimental and analytical effort in the development of a passive, free-vortex, or cyclonic separator. Various separator configurations were designed and tested using air and water and a 50w/o water-glycerin mixture. The concept is to inject a two-phase flow tangentially into a cylinder and let the flow momentum separate the gas and liquid phases into the inner and outer regions of the separator respectively.

Four flow patterns are observed. Bubbly core flow, see Figure 9, consists of bubbles flowing in a coaxially cyclonic fashion towards the center while the liquid is centrifuged out towards the side and occurs during moderate inlet velocities. A core flow, similar to Figure 10 consists of a nearly cylindrically-shaped gas core with a mixture of very small bubbles and liquid flowing around the central gas core and is usually achieved at high inlet velocities like those occurring during annular flow. Transitional flow involves a tighter rotation or nearly-cylindrical shaped agglomeration of bubbles; however, because of limited velocities, there is insufficient bubble coalescence. At low flowrates, the separator volume is too large to provide sufficient centrifugal action to achieve a decent separation and results in an amorphous mess. This last flow condition is easily remedied by reducing the volume of the separator.



Figure 9.—Bubbly core.

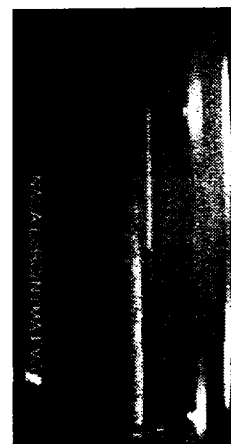


Figure 10.—Core flow.

Summary

Several experiments have been conducted for two-phase flow in microgravity through non-straight, non-cylindrical geometries. Flow through contractions illustrates that the primary driver for a flow regime transition from slug to annular flow is not coalescence but squeezing large spherical bubbles into smaller diameter tubes whereby they become cylindrical bubbles. Flow through expansions demonstrates the existence of conditions whereby a two-phase jet can

exist that is surround by a gas area. A somewhat quiescent liquid film is on the wall except for occasional interactions with the two-phase jet's unstable nature. Flow through splitting tees illustrates the dominance of the liquid momentum in determining the distribution of the phases between the two exits. Differences in flow regimes and pressure fluctuations are identified for flow through packed beds when compared to microgravity. Cyclonic separation devices show that the flow momentum can be sufficient to passively drive at least a first stage separation of the phases.

Although these studies are still, relatively speaking, in their infancy, they have provided valuable information regarding the importance of the flow momentum, and the existence of liquid dryout due to sharp corners in microgravity.

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